THE CHEMISTRY OF THE STARS AND THE EVOLU-
TION OF RADIOACTIVE SUBSTANCES

By Gilbert N. Lewis

I have been asked to present in this place an address which I gave last winter before the Astronomical Society of the Pacific. Unfortunately, I spoke at that time from few notes and no stenographic record was taken, so that it is hardly possible for me now to offer much more than an abstract of my remarks on the chemistry of the stars.

Chemistry has already learned much from astronomy. The interesting gas known as helium was so named before it had ever been obtained from terrestrial sources. It was assumed to exist in the Sun and to be responsible for certain important lines of the solar and stellar spectra. Even now in the spectrum of the corona, as it is observed during a total eclipse, and in the spectra of many nebulæ, there are numerous important lines of the spectrum which have not yet been identified with any known substance, and to account for these, two new elements, coronium and nebulium, have been postulated.

While the laboratory affords means of investigating only a minute range of conditions under which chemical reactions occur, experiments of enormous significance are being carried out in the great laboratories of the stars. It is true, the chemist can synthesize the particular substances which he wishes to investigate and can expose them at will to the various agencies which are at his command; we cannot plan the processes occurring in the stars, but their variety is so great and our methods of investigation have become so refined that we are furnished an almost unbounded field of investigation.

The views which I am to present here may seem somewhat speculative in character, but this is no longer unfashionable.

Science of the twentieth century is characterized by its audacity; indeed this is a wholesome trend, for while the sort of vague surmise which is not based upon experimental evidence nor capable of experimental test has no place in our scientific method, rational speculation must always be regarded as the advance guard of experimental science. It is my purpose in this paper to consider whether there is any evidence furnished by astronomy which may throw light upon the age-long chemical problem of the transmutation of elements, and especially to see whether conditions within the stars offer any clue to the mysterious origin of the elements which we know as radioactive.

In this inquiry it will be necessary to depend not merely upon the great mass of spectroscopic data, which after all tells us only of the conditions at the surface of Sun and stars, but it will be necessary also to follow the astronomers, Russell and Eddington, in their study of the probable conditions which prevail in the interior of the heavenly bodies.

Many years ago it occurred to me that important deductions as to the internal conditions of the stars and planets might be drawn from certain simple observations which have received surprisingly little attention. I refer to the observed densities of astronomical objects, that is, to the ratio between their mass and their volume. On the basis of spectroscopic study, together with the evidence which comes from the analysis of the meteors which occasionally find their way into the sphere of the Earth's attraction, I think we are safe in judging that the heavenly bodies are of about the same essential composition with respect to our elements (or proto-elements). Now since all matter is compressible, and since it is readily shown that enormous pressures must exist in the interior of suns and planets (see Table 1), we might predict that the largest bodies would have the highest mean density. The facts are represented in Table 2, and it will be seen that for the smaller bodies the prediction is verified. Thus the Moon, which has a small internal pressure, also has a smaller density than the Earth, and so do the other smaller planets, *Mercury, Mars* and *Venus*. But as we turn to still larger bodies we find a remarkable reversal. The heavy

planets such as *Jupiter* and *Saturn,* and also the Sun, have densities far less than that of the Moon.

Table 1

Pressures

Highest pressure obtained in laboratory,		30,000 atmospheres.
Pressure at center of:		
	The Moon,	13,000 "
	The Earth,	300,000 "
	Jupiter,	10,000,000 "
	The Sun,	1,000,000,000 "

Table 2

	Density	Diameter in Miles
The Moon, ...	3.5	2,000
The Earth, ...	5.5	8,000
Other smaller planets, ...	3.5 — 5.0	3,000 — 8,000
Larger planets, ...	1.0 — 1.8	29,000 — 86,000
The Sun, ...	1.4	900,000

There must therefore be something which counterbalances the effect of the internal pressure. At first sight it seems that some sort of shielding of gravitational force might account for the low densities of the larger bodies, but an analysis of the effect such shielding would have upon the orbits of the planets shows such an explanation to be untenable. Only one other explanation offers itself. While substances become more dense with increasing pressure, they become less dense with increasing temperature, and we know that the larger members of our solar system are hotter than the Earth. Table 3 gives an estimate of the surface temperatures of some astronomical bodies. The value for *Jupiter* is based on the observations of some astronomers that the surface of this planet, when seen through what are supposed to be rifts in the superficial clouds, appears to be incandescent.

Table 3

Temperatures

Temperature of:		
	The tungsten lamp, ...	3,000°
	The arc lamp, ...	4,000°
Surface temperature of:		
	Jupiter, ...	1,000°
	The Sun, ...	6,000°
	Hottest stars, ...	15,000°

Now while these temperatures are very large, they are by no means large enough to produce changes of density which would compensate the gigantic pressures which we have noted. Our

conclusions must of necessity be very far from quantitative. While we know the change of density with pressure over a range of a few thousand atmospheres, and the change with temperature over a range of a thousand degrees, we have no way of extrapolating with any certainty to the stupendous temperatures and pressures with which we are here concerned. But even the roughest calculation shows that to compensate for these very great pressures it would be necessary to assume temperatures of an entirely different order of magnitude from those which exist at the surface of Sun and stars. Rather we would be led to such a guess as is represented by Table 4, where the value for the internal temperature in the center of the Sun is taken to coincide with an estimate made by Eddington.

Table 4

A Rough Estimate of Internal .Temperatures

Center of Earth, ...	50,000°
Center of Jupiter	500,000°
Center of Sun (Eddington), ...	5,000,000°
Maximum stellar temperature, ...	100,000,000°

Now it will appear to some that it is absurd to postulate the existence of such almost unthinkable temperatures, not only in the depths of stellar space, but even within a few thousand miles of us in the Earth itself. But true scientific caution does not consist in refusing to accept a number merely because it is a large one, but rather it consists in weighing all available evidence and determining our present beliefs on the basis of that evidence alone. Now there is no evidence whatsoever against the assumption of such temperatures as are suggested in Table 4. On the other hand, there are several kinds of evidence in favor of such an assumption.

First we may consider the Earth itself. It is a well established fact that any deep boring into the Earth's crust brings us to temperatures much higher than those of the surface. The Earth's interior is really unexplored. The greatest depths to which we have penetrated amount to hardly more than a mile. At such a depth temperatures are sometimes found at which water boils, and although the temperature gradient is not the same in all localities, the average lies between 50° and 100° C. per mile of depth. If this rate were maintained only fifteen

miles it would lead to a temperature something like 1000° C., and although we know nothing of the qualitative laws of heat conduction at high temperatures and pressures, we may assume at least that the temperature constantly increases with the greater depth, and reaches a maximum at the center of the Earth.

Another piece of corroborative evidence is furnished by the fact that as a rule the largest heavenly bodies, in which we assume the highest internal temperatures, are also the ones which have the highest superficial temperatures.

Finally, the most conclusive evidence of the existence of these enormous internal temperatures is one brought forward by Eddington. We have seen that the pressure due to gravitation at the center of the Sun is 1,000,000,000 atmospheres. We are going to compare this pressure with what is known as the pressure of light—a comparison which at first seems ludicrous, since the pressure produced by a ray of light has been found to be so extraordinarily small that only the most refined physical instruments permit its detection and measurement. But we know that the pressure exerted by the light, or the radiant energy, which comes from an incandescent object is proportional to the amount of that energy emitted in a given time, and this rate of emission of energy from a hot body increases not proportionally to the temperature itself, but to the *fourth power* of the temperature. Thus if the temperature is increased ten-fold, the rate of emission, and therefore the pressure caused by the radiant energy, is increased ten thousand-fold. A hundred-fold increase in temperature means that the pressure is increased by the factor 100,000,000. If therefore the temperature at the center of the Sun is 5,000,000° the pressure of light is calculated to be one and one-half million atmospheres. If the temperature in the Sun were 25,000,000° the outward pressure caused by the light would amount to one thousand million atmospheres, which is the value that we have already found for the inward pressure at the center of the Sun due to gravitation. At such a temperature there would then be a complete balance between these opposing forces, and at any higher temperature

the Sun would explode, or at least would expand until a balance between the two pressures could be obtained.

Now since such a gigantic cataclysm would occur at a temperature not much above that which we have assumed for the interior of the Sun, and since we know stars whose surface temperature is very much higher than that of the Sun, indicating higher internal temperatures, we should expect to find here and there through the universe cases in which just such a phenomenon has happened. If we could find such cases it would confirm us in the opinion that stars do possess the very high internal temperatures that we are considering.

A few years ago Professor Russell of Princeton was led by his study of the stars to conclude that many of the most prominent objects in the heavens belong to a class of "giant stars,"[1] which although having no greater average mass than that of the Sun have expanded to enormous volumes. The remarkable experiments of Michelson at Pasadena have demonstrated conclusively that such giant stars, with diameters greater than the diameter of the whole orbit of the Earth, actually exist. We are thus led very directly to the conclusion that there are stars in which the internal temperature is so high that the inward pressure of gravitation is balanced by the outward pressure of radiation.

The stars do not differ greatly in absolute mass. There is no single object in the heavens whose mass is known to be more than twenty times that of the Sun. The possible gravitational pressure is therefore limited, and this in turn sets a limit to internal stellar temperatures. We seem to be safe in concluding that, unless much greater masses exist than those which have been observed, there can be no temperature in the stars as great as 100,000,000° C. However, accepting this limit, it will be allowed that conditions within the stars differ pretty largely from those which are furnished by the modest equipment of a chemical laboratory.

Whence comes the energy which maintains these high temperatures within the Earth and the stars, in spite of the great

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[1] The terms "giant" and "dwarf" stars were originally suggested by Professor Hertzsprung.

loss of energy through surface radiation? There are two possibilities. One is that the Sun and stars are continually growing colder, although the process is lengthened by internal changes. Thus at one time it was an accepted theory that the source of solar energy is the gravitational energy set free by the gradual contraction of the Sun. However, calculations have shown that this would allow for the present rate of emission for only about 300,000,000 years, and it is now believed that even the known geological epochs of the Earth have been of greater duration than this; nor does there seem to be any real evidence that during the whole course of geological time the Earth has, on the average, been growing any colder.

More recently it has been suggested that radioactive processes, which are known to occur with a very large evolution of energy, are occurring in the Sun and stars in such measure as to greatly lengthen the rate of cooling. But this assumption also would imply a slow but steady "running down" of the universe.

On the other hand, it might be assumed that the stars are not on the average becoming colder, but that they are receiving from an unknown source a quantity of energy proportionate to the energy which they are emitting. Then to account for the greater radiation and the greater internal temperature of the heavier stars it would be necessary to assume that this energy is obtained by the stars in greater amount, the greater the star's mass. Such would be the case if through all space there were passing some form of radiation (ultra X ray or ultra gamma ray radiation) unabsorbed by matter, except by a very small amount proportional to the mass. But now perhaps we are becoming too speculative, and it would be safer to return to our main theme and consider what will probably happen to chemical substances which are exposed to such temperatures and pressures as prevail in the interior of stellar bodies.

Even through the very moderate temperature range which is at our disposal in the laboratory we find very great changes occurring in chemical systems. With increasing temperature complex substances are changed to simpler substances, compounds are resolved into their elements, and the elements themselves pass from polyatomic into monatomic form. Thus at

ordinary temperatures the vapor of sulfur is largely composed of molecules of the formula S_8; at higher temperatures the molecule S_6 predominates; at still higher temperatures the molecule S_2; while at the highest attainable temperature the gas is largely dissociated into the monatomic form S.

Even the atom is capable of further dissociation, for it is composed of a positively charged nucleus surrounded by negative electrons, and one or more of these electrons may be rejected at high temperatures. Thus a neutral atom of cesium vapor, which contains one electron that is very loosely held, ionizes perceptibly at 500° to 600° C. In other words, it dissociates partly into cesium ions and free electrons, and the gas is a conductor of electricity. In other cases, where the ionization cannot be experimentally realized, we may calculate by thermodynamic methods the amount of ionization which would occur at a given high temperature, when the heat which would accompany that ionization is known. Thus we find that at the temperature of the Sun's surface most metallic vapors would be very largely ionized.

Let us visualize such processes by the aid of a model which represents the modern view of the structure of such a molecule as that of chlorine. The neutral atom of ·chlorine is believed to consist of a positively charged nucleus with a pair of electrons in the immediate vicinity. Situated farther from the nucleus is a shell of eight electrons, and outside of this is another shell of seven electrons. In the chlorine molecule one electron from each atom combines to form a pair, serving as the chemical bond which we say links together the two atoms.

In Figure 1 the crosses represent the two nuclei, each with a positive charge equal to the negative charge of seventeen electrons, and the dots represent the thirty-four electrons which make the molecule neutral as a whole. When the temperature of chlorine gas is raised to about 2000° many of the molecules are forced apart, the pair which acts as the chemical bond is disrupted, and we have monatomic chlorine. As the temperature is further raised, the electrons of the outer shell will be stripped off one by one, those of the next inner shell follow in turn, and finally at such temperatures as we may believe to exist at the

center of the Sun and stars nothing remains but the bare nuclei and free electrons. This process would be somewhat, but not largely, retarded by the high pressures which exist within the stars. We thus imagine inside the stars a very much simplified chemistry—no compound molecules of any kind, and no atoms except the positively charged nuclei of the several elements, and the free electrons.

The question, however, remains as to whether the nuclei themselves remain intact, for we now regard the nucleus itself as a composite structure. By the revival of the old hypothesis of Prout, we consider every nucleus made up of smaller aggregates, and these aggregates in turn made up of the nuclei

$$Cl - Cl$$
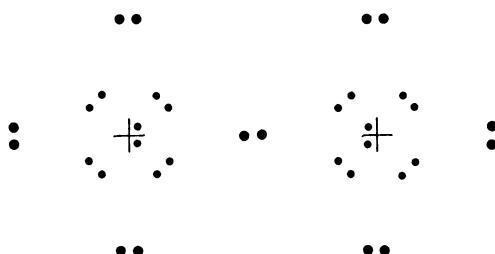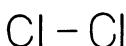
Figure 1

of hydrogen, together with certain electrons which bind the whole together. Any change which would destroy the integrity of an atomic nucleus we may speak of as a transmutation of an element.

Such transmutation is already known in the case of the radioactive substances whose peculiar properties are explained on the assumption of atomic explosions, in which helium nuclei (alpha particles) or electrons (beta particles) are shot out from the radioactive atom. Now such a process ,although it must be regarded as a chemical reaction, and subject to the laws which regulate chemical reactions, gives effects of an entirely different order of magnitude from those of any other reactions with which we are acquainted. This will be seen by comparing the

heat of radioactive change with the heats of some other types of
process which we have been discussing.

Table 5

Amounts of heat required to effect:

Dissociation of water (per gram of hydrogen)	30,000 calories
Dissociation of hydrogen into atoms	50,000 "
Ionization of hydrogen	250,000 "
Reversal of radioactivity	100,000,000 "
	to 1,000,000,000,000 "

Every reaction which occurs with an evolution of heat at
ordinary temperatures will tend to be reversed as the tempera-
ture is increased ,and this must be true also of radioactive pro-
cesses.   The newer methods of thermodynamics enable us to
calculate, from the heat of a reaction, the temperature at which
a certain degree of reversal would be observed, and although it
would be unsafe to conclude that methods which have proved
satisfactory for calculations over a range of a few thousand
degrees would retain full validity when the temperature range
is 100,000,000°, nevertheless we seem to be justified in accept-
ing in a general way the results of such thermodynamic
calculations.

Applying then these methods to the cases of radioactive
change, we are led to the interesting conclusion that a number
of radioactive changes (those associated with relatively small
heat evolution) will actually be reversed at temperatures below
the minimum temperature which we have concluded to exist in
the stars.   We may therefore feel sure that processes are occur-
ring in the stars which involve changes in the atomic nuclei,
or, in other words, which amount to the transmutation of the
elements.   And in particular we may conclude that some of our
radioactive elements would be stable at these stellar tempera-
tures, and in fact would be forming from substances which
under terrestrial conditions are the product of radioactive
decay.

On the other hand, such calculations show that for the
majority of radioactive processes, even a temperature of
100,000,000° would be by no means sufficient to cause appre-
ciable reversal, and a substance like radium would be unstable

at the center of the hottest stars just as it is on the surface of the Earth.

While therefore we may be sure that the high temperatures of the stars lead to a very different science of chemistry from that which we have developed in laboratories, we see that even the highest temperatures which, as far as we can see, can exist in the whole universe, do not suffice to explain the origin of our typical radioactive elements.   And yet these substances must have been formed in no very remote times, as astronomical and geological time goes, and are probably being formed today. Uranium, which is the parent of radium, decomposes at a rate which is extremely slow, and yet if the whole world had been composed of pure uranium one million million years ago, and none had been formed in the meantime, there would hardly be as much uranium left as we find in the Earth's crust.

Aside from the thermal energy of the stars, there is another occasional but very powerful source of energy which must not be overlooked.   The terrestrial thunderbolt is probably a puny thing compared with the electric discharges which occur in those great solar storms which are evidenced by the sun spots.   And it is not unlikely that, in such electric storms as occur on the Sun and on the stars, quantities of energy might be liberated which would suffice for the synthesis of radioactive elements. Yet it is hard to believe that so superficial and sporadic a phenomenon could account for the production of all our radioactive minerals.

However, if such sources of energy are deemed inadequate to explain the existence of radioactive substances, we must again have recourse to the hypothesis of an unknown form of energy, perhaps again some form of radiation of higher frequency than any radiation now known, permeating all space and responsible alike for the formation of radioactive elements and for the heat of the Sun and stars.   We thus find ourselves at the end of our discussion forced once more into the field of pure conjecture.